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Recent research directed toward the prediction of lateral-directional handling qualities

by L. W. Taylor, Jr. and K. W. Iliff

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

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RECENT RESEARCH DIRECTED TOWARD THE PREDICTION OF LATERAL-DIRECTIONAL HANDLING QUALITIES

by

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SUMMARY

A survey of lateral-directional handling qualities has been made for the purpose of developing a technique for predicting pilot ratings. This survey was made by obtaining pilot ratings of lateral control on a fixed-base simulator in conjunction with a color contact analog display. The effect of five lateral-directional handling qualities parameters were studied by systematically varying them over a wide range.

Forty-five charts comprise the results of this survey, however, these have been condensed into three charts to provide a rapid means for hand computing the pilot ratings. For more accurate predictions, a digital computer program was written which incorporated the data from all 45 charts.

Comparisons were made between predicted pilot ratings and those obtained in flight for several different airplanes. Although it is apparent that further extensions and improvements are needed to take into account some of the effects that were neglected in this study, such as mission, airplane type and use of rudders, it has been demonstrated that an extensive survey can be made and systematized in a way that enables it to be applied to a wide range of airplane configurations.

RESUME

Une étude des caractéristiques de maniabilité latérale et directionnelle a été faite en vue de l'élaboration d'une méthode permettant de prédire les évaluations fournies par des pilotes. Cette étude a consisté à obtenir des pilotes, à l'aide d'un simulateur à base fixe, associé à une figuration analogique par contact en couleurs, des évaluations en ce qui concerne le contrôle latéral. En les faisant varier dans une large gamme, on a pu étudier l'influence de cinq paramètres des caractéristiques de maniabilité latérale et directionnelle.

Les résultats de cette étude sont contenus dans quarante-cinq cartes, résumés toutefois dans trois cartes pour fournir un moyen rapide de calcul manual des évaluations de pilote. Pour des prédictions plus précises, un programme de calculateur digital a été établi reprenant les données figurant dans toutes les 45 cartes.

Des évaluations de pilote prédites ont été comparées à celles obtenues en vol pour plusieurs avions différents. Il apparaît que des extensions et améliorations supplémentaires seront nécessaires pour tenir compte de certains effets omis dans cette étude, tels que l'influence de la mission envisagée, du type d'avion et de l'utilisation de gouvernails; toutefois on a pu démontrer la possibilité de réaliser une étude approfondie et de la systématiser de manière à permettre son application à une large gamme de configurations d'avion.

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NOTATION

b	wing span, ft
C_{l_β}	dihedral derivative
C_{n_β}	directional-stability derivative
d	differential quantity
F_{stick}	stick force, lb
L_β	dimensional dihedral derivative, $1/sec^2$
L_{δ_a}	roll acceleration due to lateral control, $1/sec^2$
M	Mach number
N_p	yawing acceleration due to rolling velocity, $1/sec^2$
N_β	dimensional directional-stability derivative, $1/sec^2$
N_{δ_a}	yaw acceleration due to lateral control, $1/sec^2$
N'_{δ_a}	yaw acceleration due to lateral control (stability axis), $1/sec^2$
p	rolling velocity, radians/sec
p_{max}	maximum rolling velocity, radians/sec
s	Laplace transform variable
$T_{1/2}$	time required for transient oscillation to damp to one-half amplitude, sec
T_ϕ	time required to bank ϕ degrees, sec
V	velocity, ft/sec
V_i	indicated velocity, knots
α_0	angle of attack of the principal X-axis, radians
β	sideslip angle, radians
β_{max}	maximum sideslip angle, radians
δ_a	aileron deflection, radians
$(\delta_a)_{max}$	maximum aileron deflection, radians

δ_{stick}	control-stick deflection, inches
ζ_d, ζ_ψ	damping ratio of Dutch roll oscillation
ζ_ϕ	damping ratio of numerator of roll-transfer function
τ_S	spiral mode time constant, sec
τ_R	roll mode time constant, sec
ϕ	bank angle, radians
ω_d, ω_ψ	Dutch roll frequency, radians/sec
ω_θ	pitch frequency, radians/sec
ω_ϕ	frequency of numerator of the roll-transfer function, radians/sec

RECENT RESEARCH DIRECTED TOWARD THE PREDICTION OF LATERAL-DIRECTIONAL HANDLING QUALITIES

Lawrence W. Taylor, Jr and Kenneth W. Iliff

1. INTRODUCTION

Understanding the relationships between the stability and control characteristics of airplanes and the pilot assessment of the handling qualities has proved to be a difficult and continuing problem. Although many investigators[1-14] have studied the effects of a multitude of parameters, such as those shown in Figure 1 for lateral-directional stability and control, advances in airplanes have increased the complexity of the problem, in particular, the lateral-directional modes of control. Consequently, the results of these independent investigations have not been fitted into a consistent framework of knowledge with broad applicability. As a guide, the preliminary designer is often forced to use results for a class of airplane different from that with which he is concerned because of the limited information available. Later in the design, after a configuration has been selected and tested in the wind tunnel, the designer probably would use a flight simulator to assess handling qualities. There is, however, a definite need for a quicker and more economical means of predicting the handling qualities of an airplane as early in the design phase as possible.

With this need in mind, the NASA Flight Research Center undertook a general study of lateral-directional handling qualities with the goal of developing criteria that are more generally applicable than those now available.

2. APPROACH TO THE STUDY

Many parameters influence lateral handling qualities; thus certain restrictions were necessary to make the study feasible. Considering the transfer function of bank-angle response to aileron deflection, as shown in the following equation, seven parameters are involved because of the seven independent coefficients in the numerator and denominator:

$$\frac{\phi(s)}{\delta_a(s)} = \frac{L_{\delta_a}\left(s^2 + 2\zeta_\phi\omega_\phi s + \omega_\phi^2\right)}{\left(s + \frac{1}{\tau_S}\right)\left(s + \frac{1}{\tau_R}\right)\left(s^2 + 2\zeta_d\omega_d s + \omega_d^2\right)} .$$

However, with the usual restriction of neutral spiral stability which is usually adequate for all except low speeds, the number is reduced to 6. Also, the damping terms for both the numerator and denominator second-order factors and the roll damping are highly dependent on velocity. It follows that these parameters may be considered to be dependent by making the roll damping proportional to $2\zeta_d\omega_d$, and $2\zeta_\phi\omega_\phi$ equal to $2\zeta_d\omega_d$. With these additional restrictions, only four independent parameters remain to be considered in the bank-angle transfer function. The sideslip transfer function can be simplified to the following equation and the only additional parameter introduced is L_β:

$$\frac{\beta(s)}{\delta_a(s)} = \frac{-N'_{\delta_a}}{(s^2 + 2\zeta_d\omega_d s + \omega_d^2)} = \frac{L_{\delta_a}(\omega_d^2 - \omega_\phi^2)}{L_\beta(s^2 + 2\zeta_d\omega_d s + \omega_d^2)} .$$

The parameter ω_d, which appears in both transfer functions, is simply the Dutch roll natural frequency in radians per second and is related to the directional stability and dihedral parameters, N_β and L_β. The term ω_ϕ is the control-coupling parameter, which includes the roll-control derivatives L_{δ_a} and N_{δ_a}.

The effect of these five parameters on lateral-directional handling qualities was studied by utilizing the simple, direct approach of obtaining pilot ratings of lateral control on a fixed-base simulator (Fig. 2) as the parameters were systematically varied over a wide range. A color contact analog or television display was used from which the pilot could interpret bank, heading, and sideslip angles. Instruments were also provided to give precise indications of bank, heading, and sideslip angles and also roll rate. Pilot evaluations were based on the following modified Cooper rating scale[10,15]:

Numerical Rating	*Category*	*Adjective Description within Category*
1 2 3	Acceptable and satisfactory	Excellent Good Fair
4 5 6	Acceptable but unsatisfactory	Fair Poor Bad
7 8 9	Unacceptable	Bad Very bad Dangerous
10	Unflyable	

3. DISCUSSION OF RESULTS

3.1 General Survey Results

The results of the survey have the format shown in Figure 3; pilot ratings are presented as functions of ω_ϕ and ω_d, with control power, damping, and dihedral effect as constant parameters. Where ω_ϕ is equal to zero, the coupling effect is so severe that the airplane yaws and banks but does not continue to roll. Where ω_ϕ equals ω_d along the diagonal, essentially no sideslip is induced. This condition is usually the most desirable. Values of ω_ϕ exceeding ω_d cause sideslip to be induced in such a manner that the pilot tends to augment the Dutch roll oscillation while attempting to stabilize bank angle. Extreme ratios of ω_ϕ to ω_d make control impossible.

Figure 4 is an example of the 45 plots that comprise the results of the survey. Note that the constant pilot-rating contours are radial lines for $\omega_\phi + \omega_d$ greater than 3.0, thus making it possible to speak of the more familiar ratio ω_ϕ/ω_d. Usually, a ratio of ω_ϕ/ω_d equal to 1.0 is most favorable, with smaller ratios resulting in adverse yaw and roll sluggishness and ratios greater than 1.0 resulting in favorable yaw and pilot-induced oscillations. For this case of moderate damping, the pilot ratings are not particularly sensitive to small changes in the ratio of ω_ϕ to ω_d. Figure 5 shows an identical set of characteristics except for much less damping. In this instance, an ω_ϕ/ω_d ratio of only 1.1 is uncontrollable. A comparison of the two figures shows the marked effect of damping on a pilot's acceptance of control coupling of the type that causes pilot-induced lateral-oscillation tendencies.

Although it would be possible to use these plots to predict lateral-directional pilot ratings by interpolating between charts for a particular application, the procedure would be tedious and time-consuming. To provide a more rapid means for hand-computing the pilot ratings, much of the information in the full set of charts has been reduced to the three summary charts in Figures 6(a) to 6(c). Lines of constant pilot ratings are presented as a function of the ratio of ω_ϕ/ω_d and lateral control power for the restricted ranges of ω_ϕ plus ω_d, and L_β, and for a given level of damping. Several generalizations can be made about the results shown. First, for all but the lower values of control power $L_{\delta_a}(\delta_a)_{max}$, the most favorable pilot ratings occur when ω_ϕ equals ω_d. For the very low and vanishing levels of control power, favorable sideslip, indicated by $\omega_\phi/\omega_d > 1.0$, is preferred, since it compensates to a degree for the very sluggish roll response. This trend is especially evident for the highest level of damping. For very large values of control power, the extreme sensitivity precludes satisfactory ratings even for ω_ϕ/ω_d equal to 1.0. Increased damping would result in more favorable pilot ratings, however.

The summary charts of Figure 6 can be used to predict lateral-directional pilot ratings by interpolating between the appropriate charts. In the event that a rating greater than 10 is indicated by one of the charts, an extrapolated value greater than 10 should be used in the interpolation between charts. Best results can be obtained, however, when the data for the full set of 45 charts have been mechanized in a digital-computer program. Such a program now in use at the Flight Research Center is illustrated by the block diagram in Figure 7. As shown, information in the 45 plots of the pilot-rating survey and several sets of airplane characteristics, stability derivatives, moments of inertia, and the like are fed into a digital computer. The digital computer then computes the dimensional stability derivatives and numerous parameters of interest and predicts pilot ratings by interpolating over the five parameters of the survey. The greatest value of these predictions is that a large number of airplane configurations and flight conditions can be assessed quickly and at little cost. This feature is particularly important to the preliminary designer and the flight-test engineer.

3.2 Comparison of Predicted and Flight Ratings

The method described has been used successfully as an aid during the design of controls for a lifting-body research vehicle. However, the results obtained are considered to be preliminary. For significance, the computed pilot ratings must compare well with those obtained in flight or from a flight simulator. At present, the method is being tested by comparing the predicted pilot ratings with ratings obtained in flight for many different aircraft. Although the rudder was not used in the subject simulator survey, there was no restriction on its use during the flight investigations for which comparative pilot ratings are presented herein.

In Figure 8, predicted pilot ratings of the X-15 airplane are compared with actual pilot ratings from flight and the X-15 flight simulator. The comparison is for the airplane with the lower ventral stabilizer on and the dampers off. The predicted pilot ratings do well to show not only the general trends with Mach number but also the average levels, except at a Mach number of 3.5. A discrepancy of the magnitude shown can easily exist when a situation such as this borders on being uncontrollable because of pilot-induced oscillations. In this instance, small differences in damping or the ratio ω_ϕ/ω_d can result in large differences in pilot rating. In Figure 9, the correlation of the ratings for the X-15 with dampers on is good; the predicted ratings are only slightly more favorable than the average ratings from flight and simulator. Additional comparisons of flight, simulator, and predicted pilot ratings are made in Reference 16.

In Figure 10, flight and predicted ratings are compared for the F-104 airplane with all dampers off. The correlation is good at the high Mach numbers, but the predicted ratings are optimistic at the lower Mach numbers. The discrepancy of about 2.5 rating units at a Mach number of 0.9 warrants further investigation.

Ratings are compared in Figure 11 for the T-33 airplane. Again, the predicted pilot ratings are more favorable; the difference between the predicted and flight ratings is about 1.5 units at the higher speeds. Predicted pilot ratings that are usually optimistic would indicate that possibly some other effect not duplicated in the prediction method, such as control-stick friction, might be influencing the pilot ratings in flight. Uncertainty of the aerodynamic and mass characteristics of the airplane would also cause an apparent error in the predicted pilot ratings.

The comparison shown in Figure 12 is for a different class of airplane, the 990 jet transport. Although flight pilot ratings are available from only one pilot, correlation of the predicted pilot ratings with those obtained in flight is good. This agreement is somewhat surprising, since no consideration is given to airplane type in the prediction technique. Figure 13 shows a similar comparison for a transport airplane that has seen many years of service, the C-47. The gradual trend in pilot rating with airspeed was predicted, but the level predicted is about 2.5 units less favorable than that indicated by the average flight ratings. One reason for the discrepancy is that the use of the rudder was not permitted in the survey on which the predictions are based; whereas, the rudder is effective on the C-47 in counteracting adverse yaw and was used in flight. It is evident, in this case, that the effect of the use of rudders is a needed extension to the present pilot-rating-prediction method.

In Figure 14, pilot ratings from flight are compared with those predicted for a light transport, the Aero Commander. As shown, the overall level of pilot rating was predicted fairly accurately, being pessimistic by about 1 unit at the higher speeds.

4. CONCLUDING REMARKS

Although this technique of predicting pilot ratings has met with some success, it is apparent that improvements are needed. The effects of rate coupling, mission and airplane type, controller friction and forces, the use of rudders, and the size of the pilot's display all need to be considered in a more sophisticated form of pilot-rating-prediction technique. Perhaps more important than the results shown for the present form of the technique is the demonstration that such an extensive survey can be made and systemized in a way that enables it to be applied to a wide range of airplane configurations. If extensions and improvements in the method can continue to be made, the capability indicated in Figure 15 may someday be available. Predicted pilot ratings will be computed as a function of the airplane dynamics, mission, and display as well as the controller characteristics and motion effects for each mode of control. As such a capability is developed, the designer, the writer of specifications, and the flight-test engineer will have a tool that becomes more accurate and more inclusive as the technique is improved.

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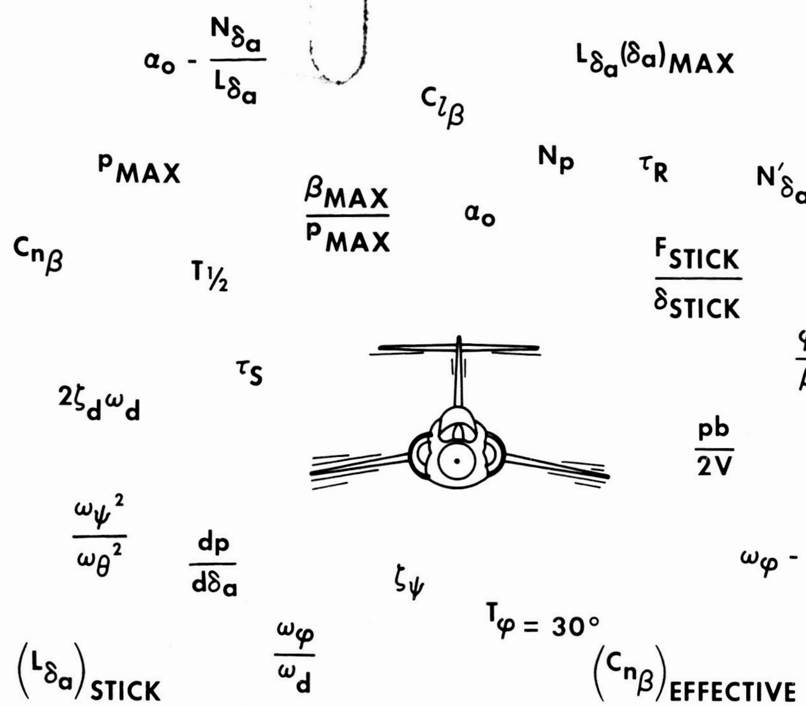


Fig. 1 Lateral-directional parameters used in various handling-qualities studies

Fig. 2 Simulator used in the survey

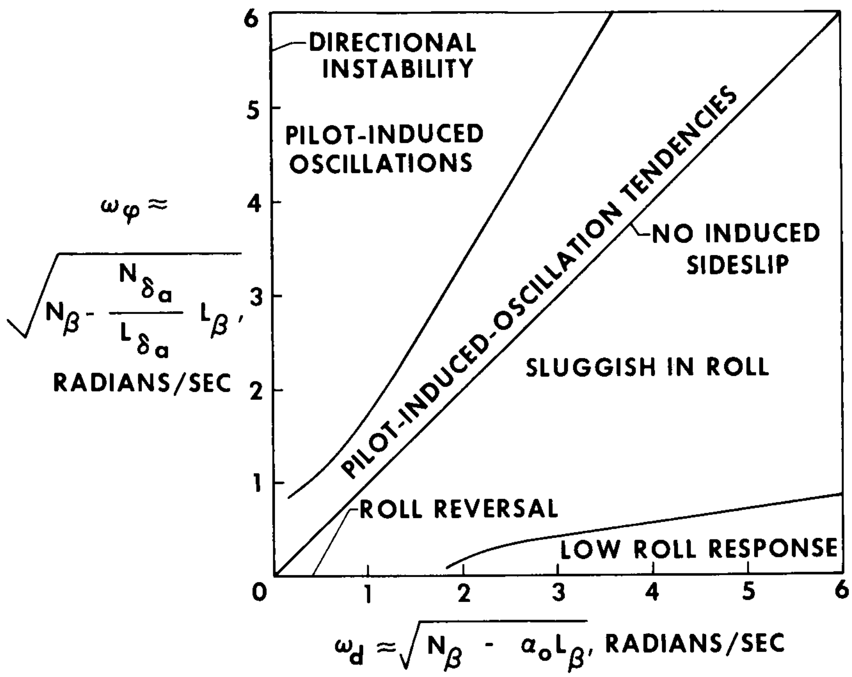


Fig. 3 General effects of ω_ϕ and ω_d on lateral-directional handling qualities

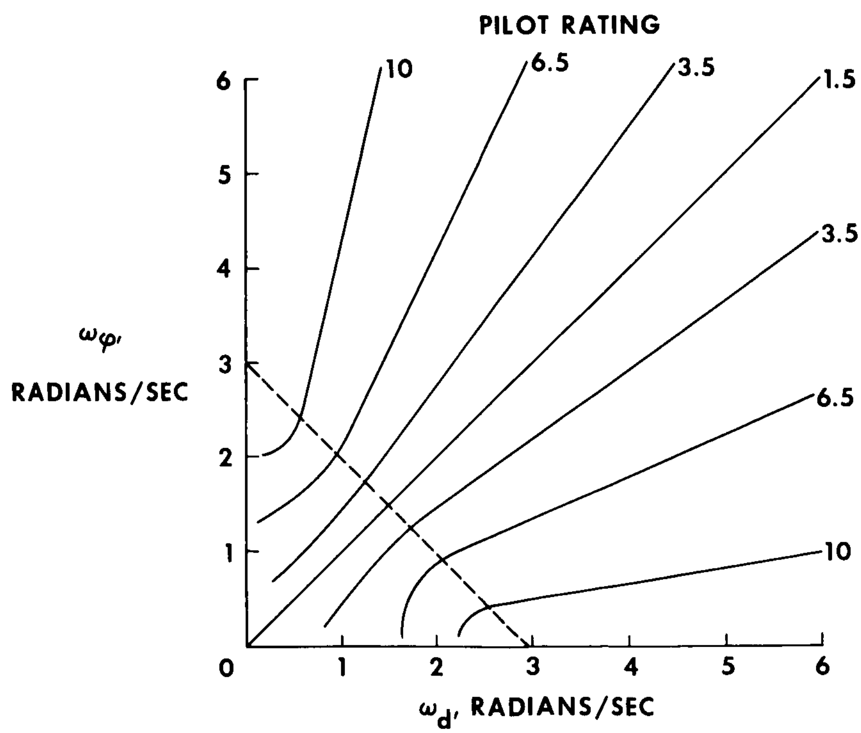


Fig. 4 Pilot-rating-prediction chart for moderate damping. $2\zeta_d\omega_d = 1$; $1/\tau_R = 4$; $|L_\beta| = 30$; $L_{\delta_a}(\delta_a)_{max} = 10$

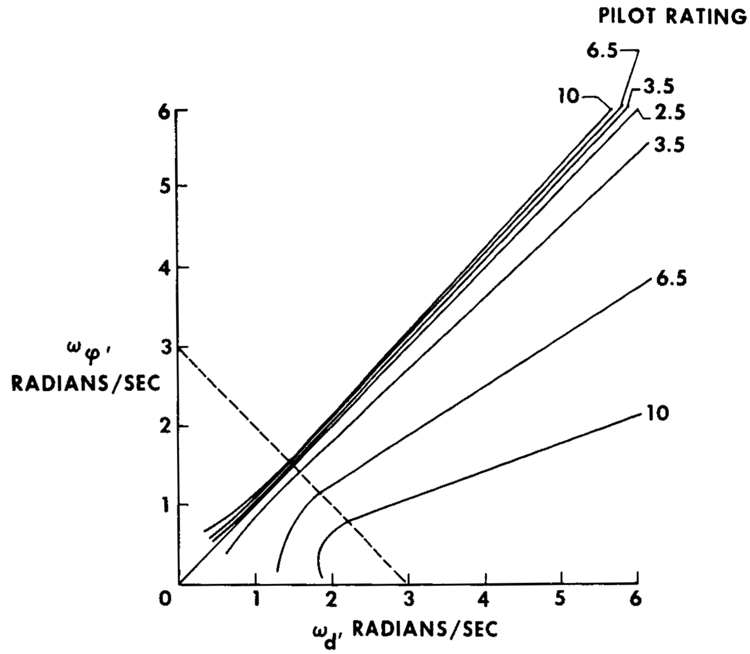
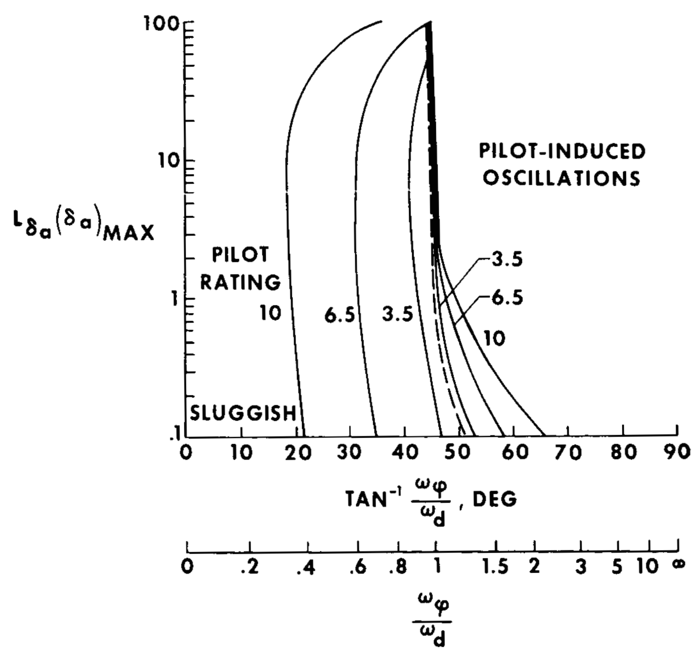
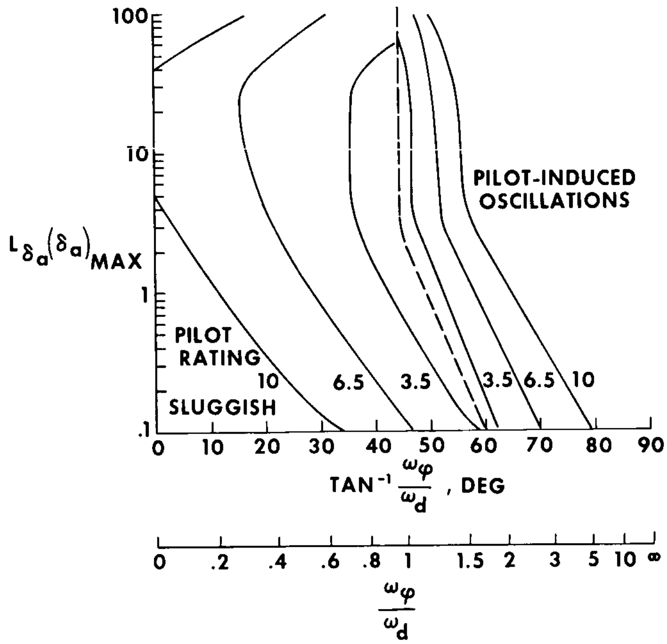


Fig.5 Pilot-rating-prediction chart for very low damping. $2\zeta_d\omega_d = 0.025$; $1/\tau_R = 0.1$; $|L_\beta| = 30$; $L_{\delta_a}(\delta_a)_{max} = 10$

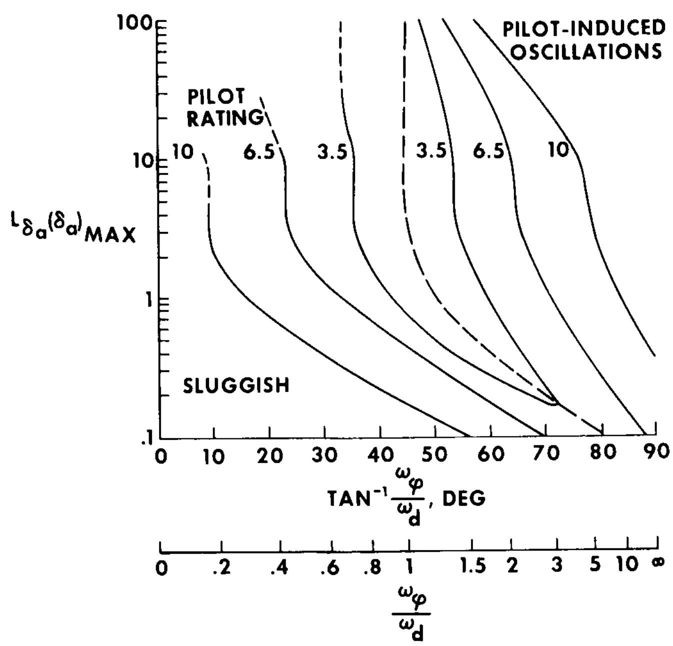


(a) Very low damping, $2\zeta_d\omega_d = 0.025$, $1/\tau_R = 0.1$

Fig.6 Summary charts for predicting pilot ratings. $\omega_\phi + \omega_d > 3$; $L_\beta > 10$
(Continued)



(b) Low damping, $2\zeta_d\omega_d = 0.25$, $1/\tau_R = 1$



(c) Moderate damping, $2\zeta_d\omega_d = 1$, $1/\tau_R = 4$

Fig. 6 Summary charts for predicting pilot ratings. $\omega_\phi + \omega_d > 3$; $L_\beta > 10$ (Concluded)

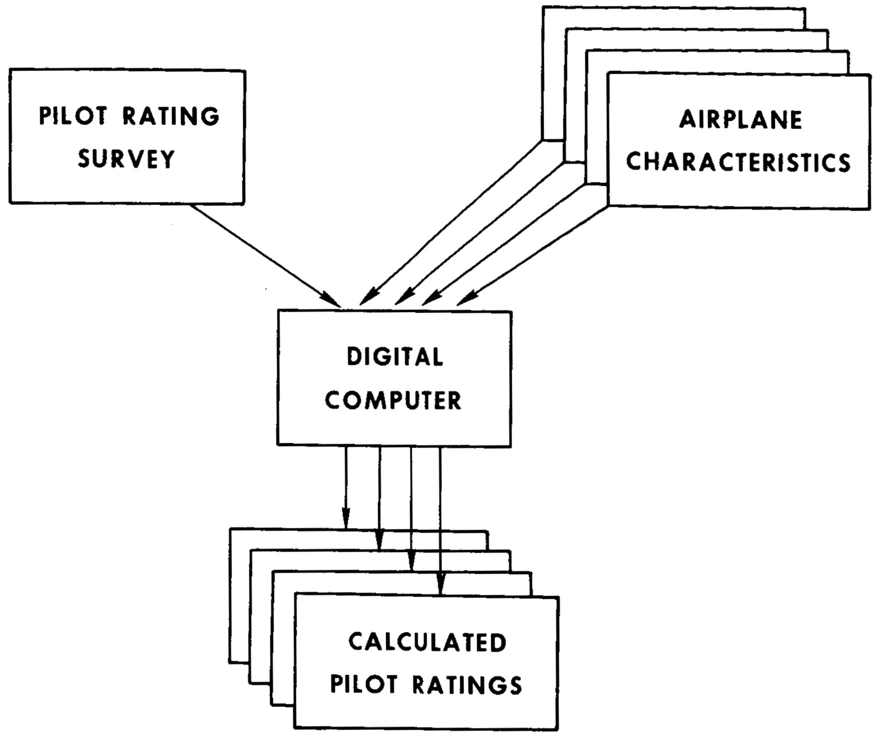


Fig. 7 Pilot-rating-prediction technique using a digital computer

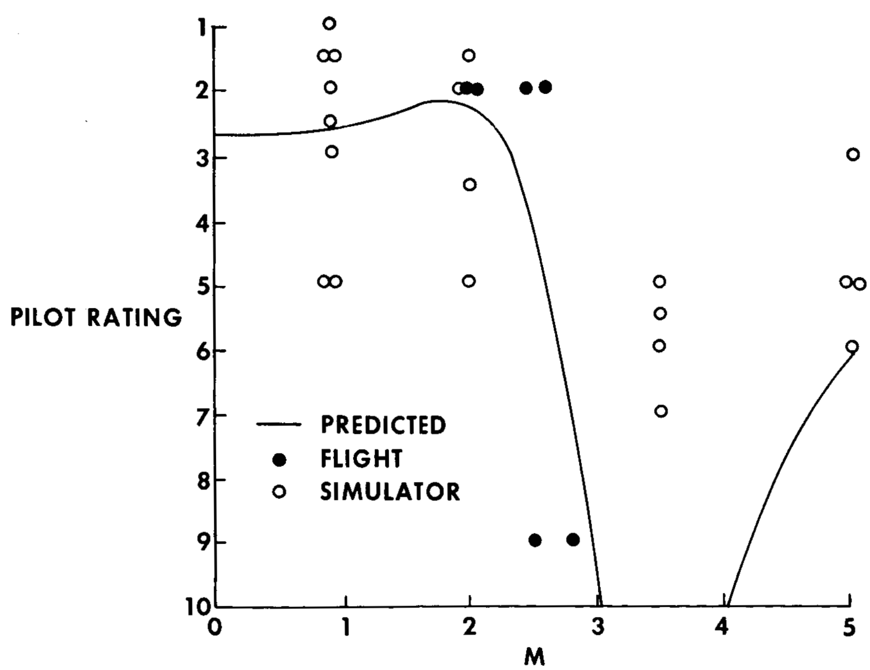


Fig. 8 Comparison of the predicted and actual pilot ratings for the X-15 airplane with dampers off and ventral on at an angle of attack of approximately 6^{0}

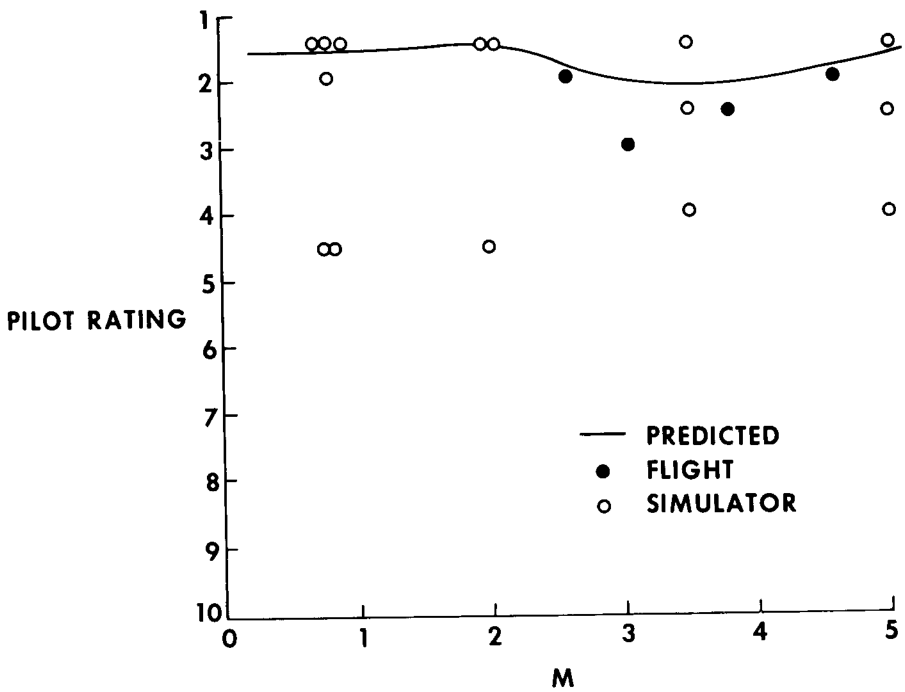


Fig. 9 Comparison of the predicted and actual pilot ratings for the X-15 airplane with dampers on and ventral on at an angle of attack of approximately 6^{0}

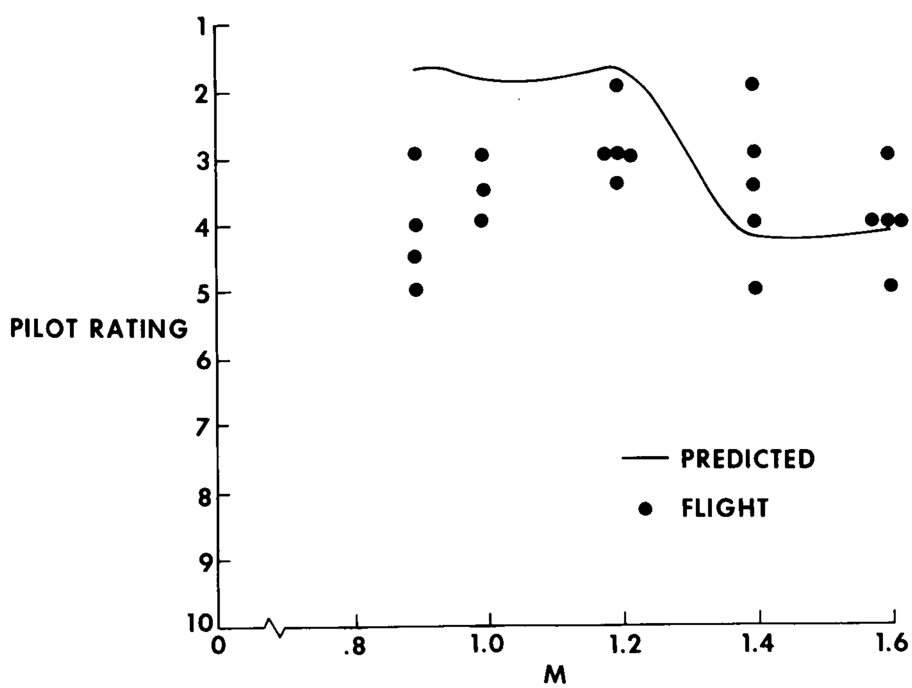


Fig. 10 Comparison of the predicted and actual pilot ratings for the F-104 airplane with dampers off

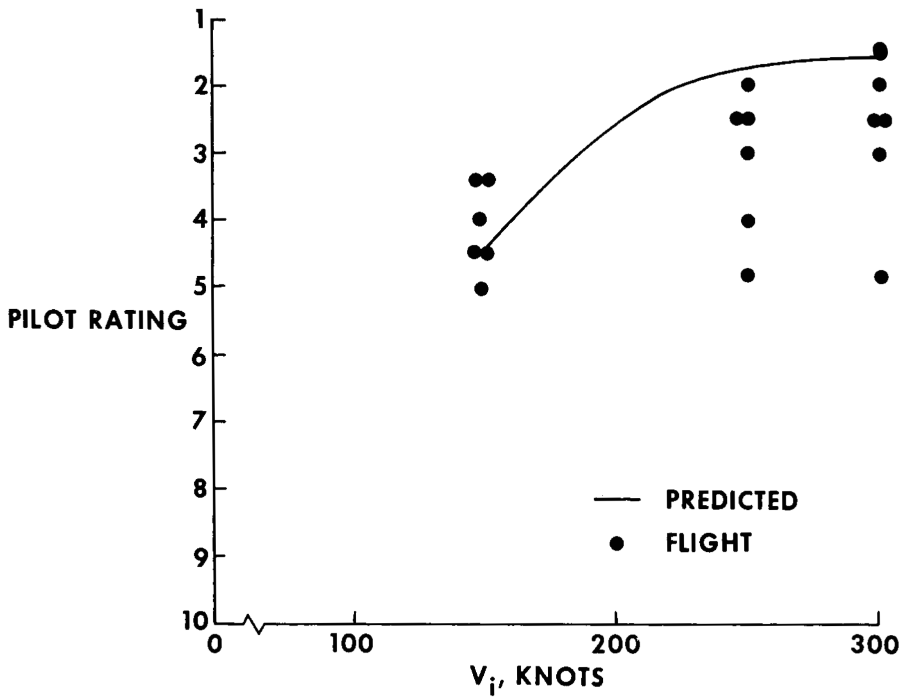


Fig. 11 Comparison of the predicted and actual pilot ratings for the T-33 airplane

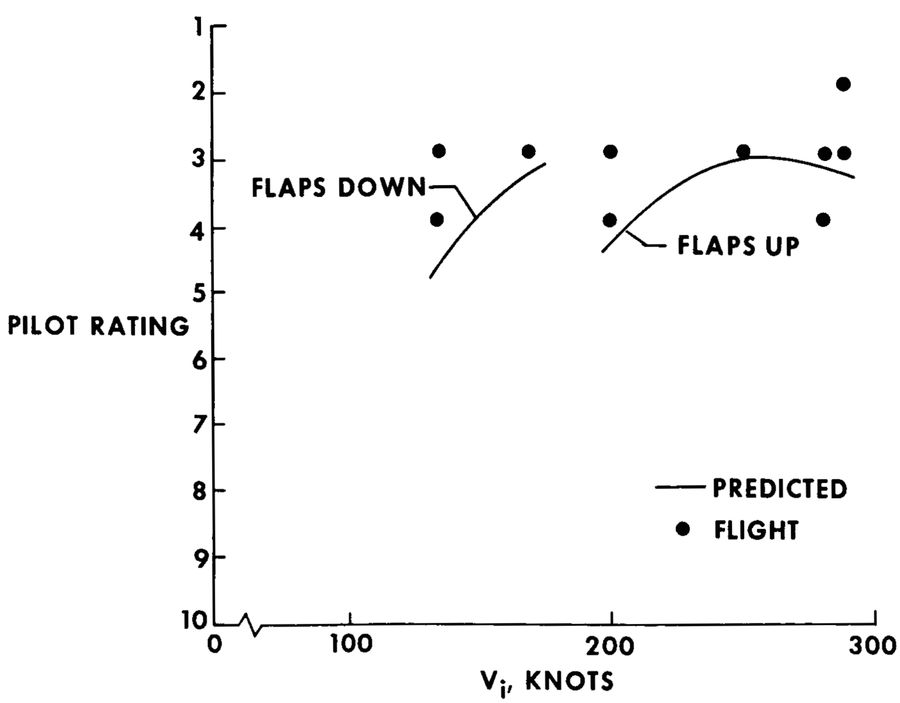


Fig. 12 Comparison of the predicted and actual pilot ratings for the 990 jet transport

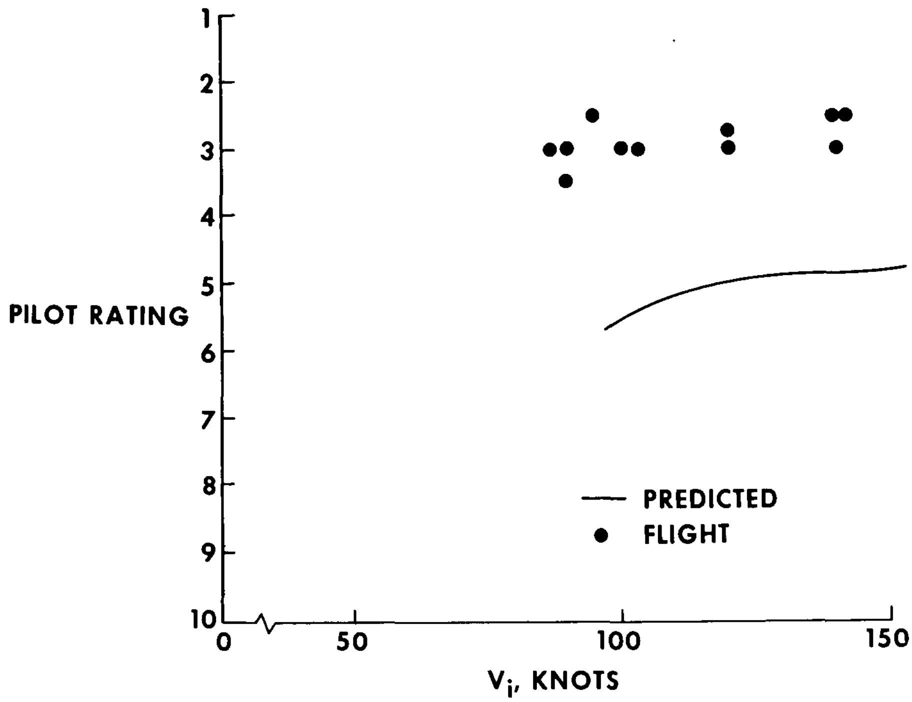


Fig. 13 Comparison of the predicted and actual pilot ratings for the C-47 airplane

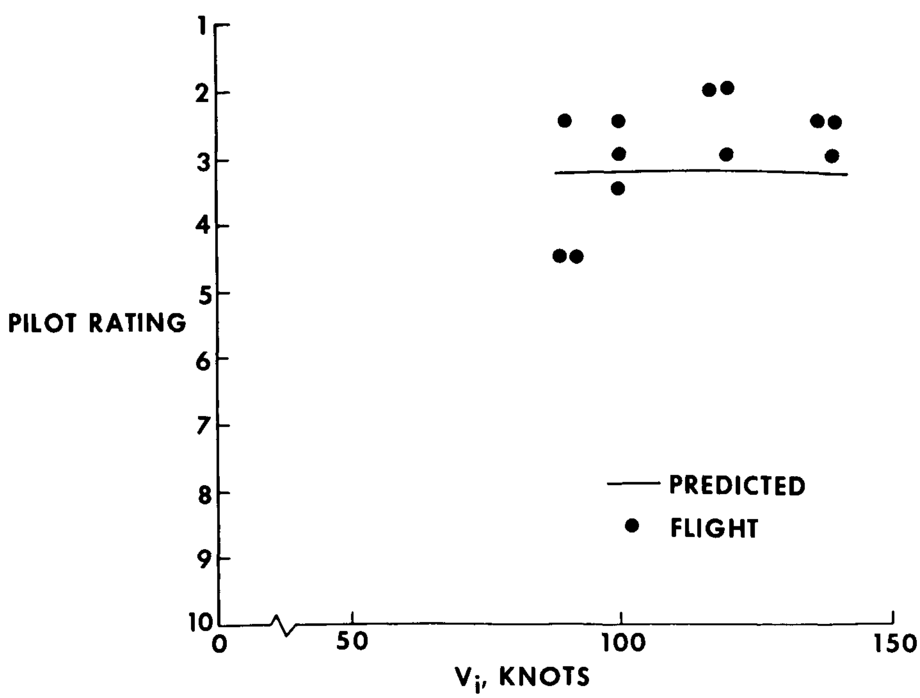


Fig. 14 Comparison of the predicted and actual pilot ratings for the Aero Commander airplane

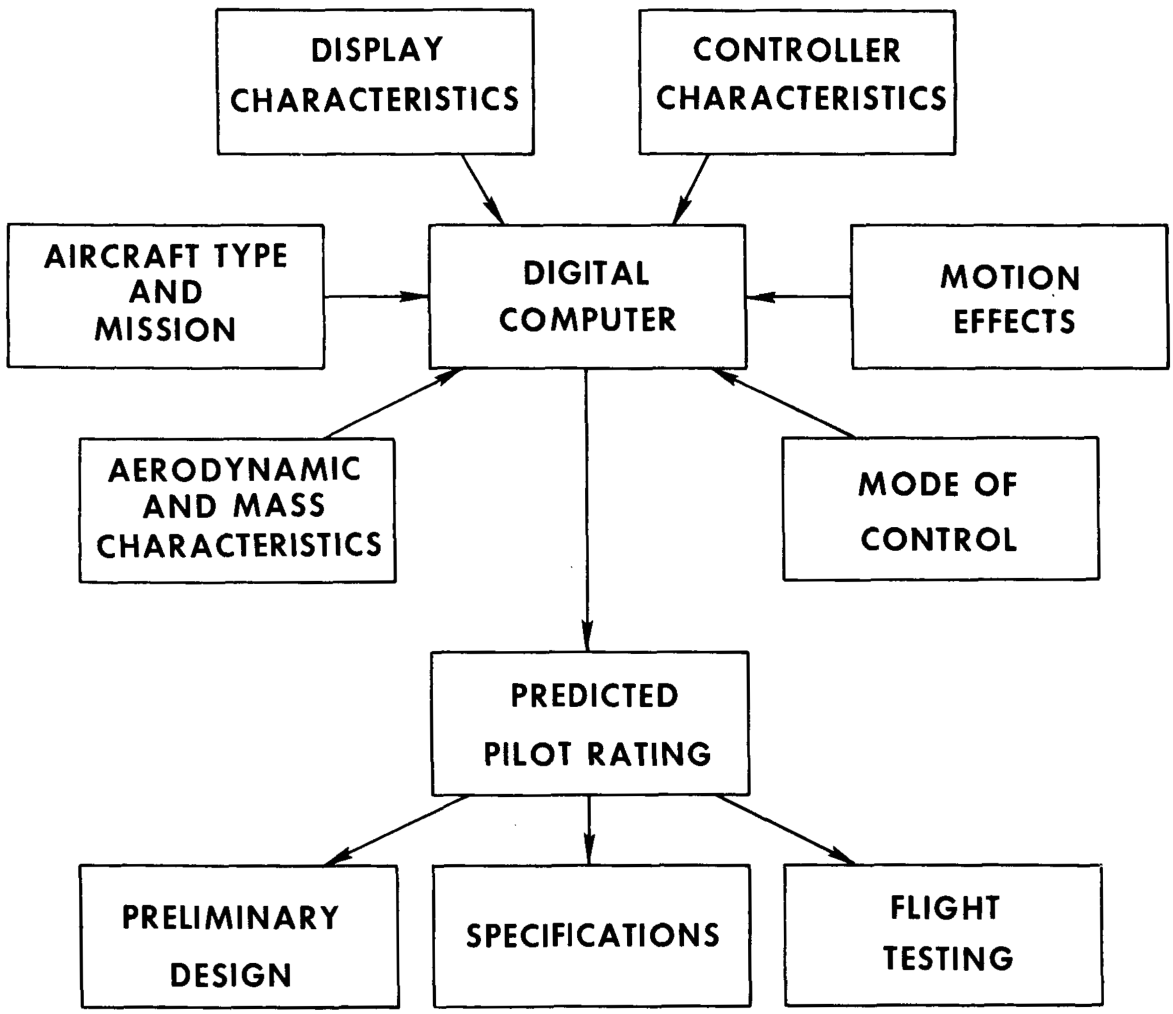


Fig. 15 Ultimate goal of the pilot-rating-prediction method

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